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A High Sensitive Micro-Seismic Fiber Bragg Grating(FBG) Sensor System

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Abstract

A high sensitive micro-seismic fiber Bragg grating (FBG) sensor system based on narrow line width distributed feedback (DFB) laser is realized by using filtering demodulation. Sensitivity of micro-seismic FBG sensor lies on the structure of the sensor shell and the shape of the reflectivity spectrum of FBG. Experiments on the sensor system's frequency character have been done. Results show that this sensor has the smallest acceleration of 1mm/s^2. The experiments on coal mine exhibit that the sensor can be used to measure micro-seismic sigmals. So the FBG sensor is feasible to have practical use to measure micro-seismic signals because the sensor has high sensitivity and is easy to be fabricated, it has good low frequency response and the interrogation system is simple, low cost.

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Keywords: FBG, DFB laser, interrogation, micro-seismic, acceleration, sensor, modulation

1. Introduction

Recently, due to their immunity to Electro Magnetic Interference, electrically passive operation,

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possibility of working in chemistry environment and capability of multiplexing, the fiber Bragg grating is focused more and more. FBG micro-seismic sensors therefore have wide prospect in use in mine safety monitoring, oil exploration, structural health monitoring and various vibration situations. The key

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technology on FBG micro-seismic sensors is how to get rhe micro-seismic signals from reflectivity spectrum of FBG modulated. The sensors measuring microseism signals needs high resolution, quick measurement and low cost. But all these conditions are main problems currently.

Commonly, there are interrogation methods such as M-Z interference[1], FBG filtering[2], F-P filtering[3], tunable light[4], DWDM interrogating[5], acoustic tuned integrated optics filter[6](AOTF). These schemes have been generally used for either static or dynamic measurands. Here, interference has very high sensitivity, but it also has many disturbances, such as temperature, vibration. The filtering methods have the merit of quick measurement, low cost and simple circuit process. Many optical elements have the characteristic of linear filtering, such as FBG, long period fiber grating, DWDM, super fluorescent fiber source[7], high birefringence fiber Sagnac loop mirror[8]. Here the FBGs have high sensitivity as they have steeper edge.

In this paper, a new design of filtering interrogation system for FBG micro-seismic sensor is presented, using a narrow line width distributed feedback laser whose temperature is controlled by SCM. The factors influenceing the sensitivity of the FBG sensor are analysised. Experiments on the sensor system's frequency characteristic have been done, the results show the sensitivity can reach 1mm/s^2.

2. Working Principle

The interrogation principle depends on intensity modulation of narrow line width DFB laser, when a reflection or transmission spectrum curve of an FBG moves due to the strain which is caused by vibration or acceleration, as shown in Fig.1. In order to demodulate the wavelength changes of FBG using DFB laser, the output wavelength of DFB laser must match the Bragg reflection wavelength of FBG.

When the wavelength of FBG sensor changes $\Delta\lambda$ due to strain, the reflectivity changes Δs, so the change of light intensity is $I_{in}\Delta s$[9]. In the measuring range, the $\Delta\lambda$ is relatively small. According to the principle of small-signal model, Δs and $\Delta\lambda$ have a linear relationship. In addition, because the output current of the photo detector and the intensity of the input light constitute a linear relationship, the output current signal can be expressed as follows:

$$I = \alpha \times (I_0 R + \beta I_0 \Delta\lambda) mA \tag{1}$$

Where α is the attenuation coefficient of the fiber cable, A is responsibility of photo detector, I_0 is output power of DFB laser, R is the reflectivity of FBG when the wavelength of DFB is in the -3dB reflectivity spectrum of FBG, m is system noise caused by cirlulator, FBG sensor and optical fiber, $\beta = \frac{\Delta s}{\Delta\lambda}$, $\Delta\lambda = 0.78 \cdot \varepsilon_x \lambda_B$[10], where ε_x is the axial strain of the fiber:

Then the system output can be denoted as:

$$I = \alpha \times \cdot (R + 0.78 \beta \lambda_B \varepsilon_x) m I_0 A \tag{2}$$

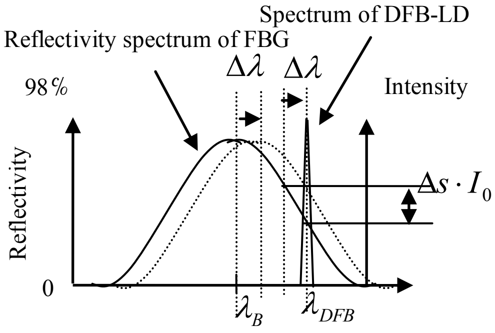


Fig. 1 Interrogation principle of the system

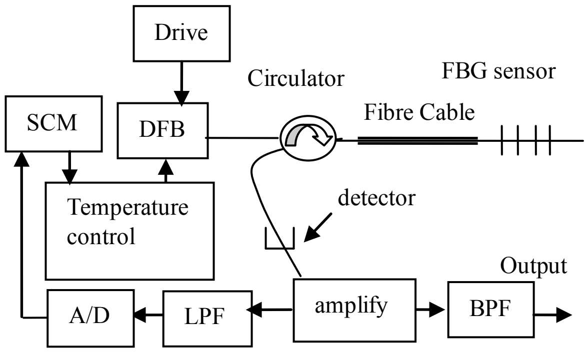


Fig.2 Schematic diagram of the interrogation system

Based on this idea, we designed the demodulation system[11], as shown in Fig. 2. Light from the DFB laser goes to the input port of the circular, the light output from this circular comes into the fibre cable and the sensing FBG. Light reflects back from sensing FBG when its wavelength located in the vicinity of the center wavelength of FBG sensor, and then comes to the other optput port of the circular to the PD where it is converted to current. One signal by band-pass filter of the system after amplified by the preamplifier is collected by NI-DAQ and then analyzed and processed by LabVIEW in PC; another signal by low-pass filter are converted to digital signals and feed back to single chip microcomputer (SCM). The SCM outputs control single to adjust the temperature of DFB laser, so that the output wavelength of DFB laser can be located in the range of the reflection of the FBG.

3. Sensitivity Analysis of Micro-seismic FBG Sensor system

The sensitivity of micro-seismic FBG sensor system lies on the structure of the sensor shell and the shape of the reflectivity spectrum of FBG. The structure of the sensor shell is composed of cantilever beam, film, reinforced beam,mass and case.The sensor model is shown in Fig.3. the cantilever beam is fixed to the shell, a reinforced beam and the cantilever beam are fixed together. FBG is fixed between reinforced beam and shell, and it must be pre-stressed. In order to enhance the sensitivity, an inert mass is attached at the end of cantilever beam. When vertical direction acceleration comes into being, the inert mass will drive cantilever beam swaying right and left. Then FBG will be stretched and compressed, and the wavelength of FBG will be changed.

The sensitivity coeficient of the sensor is:

$$K = 0.78\lambda_B \bullet \frac{a}{bl\omega_0^2} = 0.78\lambda_B \bullet \frac{a}{bl} \bullet \frac{m}{k_2 + (a/b)^2 k_1} \tag{3}$$

The inherent frequency is:

$$\omega_0 = \sqrt{\frac{k}{m}} = \sqrt{\frac{k_2 + (a/b)^2 k_1}{m}} \tag{4}$$

Where k_1 is the elasticity coeficient of the fiber, k_2 is the elasticity coeficient of the structure, m is the mass.

From Eq.(3) we can know the sensitivity of FBG sensor is related on the thickness of the film and the mass. The thinner the film's thickness is and the heavier the mass is , the higher the sensitivity of FBG sensor.is , but the lower inherent frequency is. Fig.4 shows the frequency reponse of the FBG sensor when film's thickness is 0.2mm and 0.5mm. While the film's thickness is 0.2mm, the sensitivity is 400pm/g and when the film's thickness is 0.5mm, the sensitivity of sensor is 102.5pm/g.

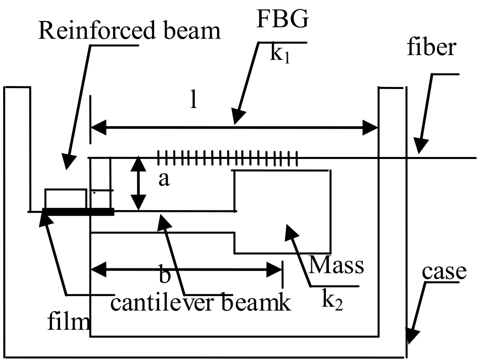


Fig.3 Acceleration sensor model

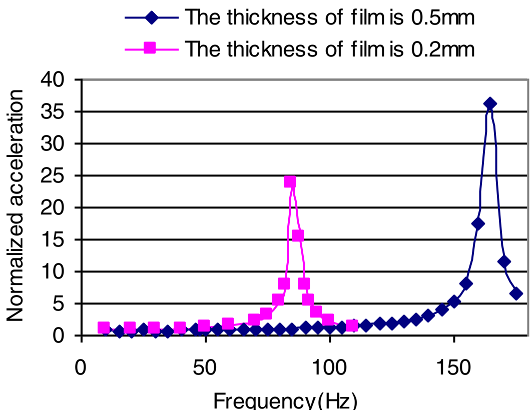


Fig.4 The frequency reponse of the sensor with different film

The shape of the reflectivity spectrum of FBG affects the reflectivity of the FBG at different wavelength. So the coefficient β of different FBG is different. Fig 5 and Fig6 show the reflectivity spectrum of FBG2 and FBG3, the change of wavelength of the gradient side is 0.08nm and 0.12nm separately. Table1 shows the steeper the gradient side is, the higer the sensitivity of FBG sensor system is, and the higher the resolution of the system is. Here $\Delta\lambda$ is the change of wavelength of the gradient side, K is the sensitivity of the sensor, r is the resolution of the system, h is the thickness of the film, f_0 is the inherent frequency, S is the sensitivity of the sensor system, a_{max} is the maximum measurable acceleration of the system. Table 1 also shows the higher the sensitivity of FBG sensor system is, the smaller the maximum measurable acceleration of the system is.

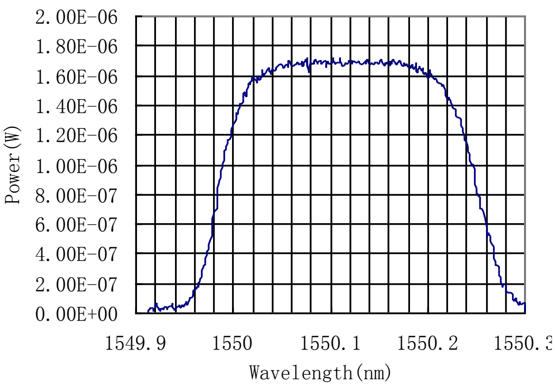


Fig.5 Reflectivity spectrum of FBG2

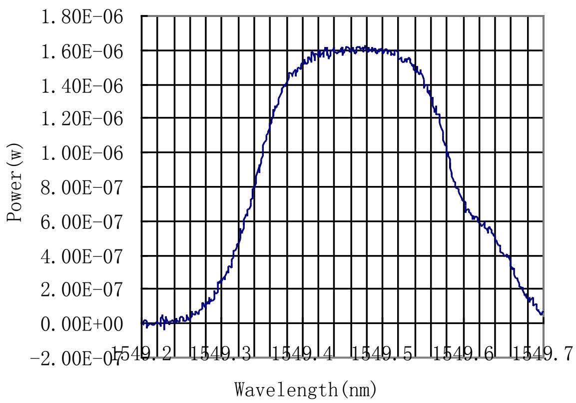


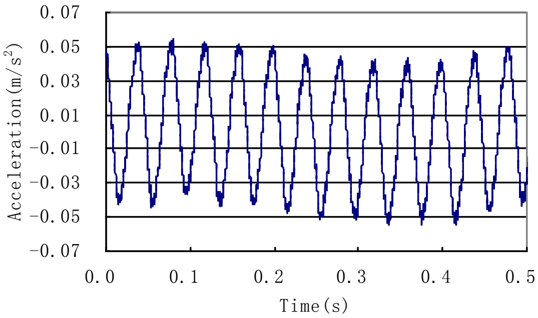
Fig.6 Reflectivity spectrum of FBG3

Table 1

	$\Delta\lambda$ (nm)	S(V/m/s^2)	r(mg)	h(mm)	f_0(Hz)	K(pm/g)	a_{max}(mg)
FBG1	0.08	6.5	0.4	0.5	165	102.5	292.5
FBG2	0.08	40	0.1	0.2	85	400	75
FBG3	0.12	12	0.3	0.2	95	330	121

4. Test Results in Laboratory

Vibration experiments were done by B&K4808 exciter, which applied vibration to the sensor, and we get the output of the system under different frequency and certain acceleration. Fig.7 shows the output signal of FBG2 sensor system and standard sensor system， when the sensor is applied with 20Hz, 48mm/s^2 acceleration. Fig.7.(a) represents the time domain output of the standard sensor of the B&K4371. Fig.7.(b) represents the time domain output of the FBG system. Influenced on the alternating current, the exciter outputs useless signals whose frequency is 50Hz, 100Hz, 200Hz, so the signals detected by the standard sensor and the FBG sensor contain these noise signals.



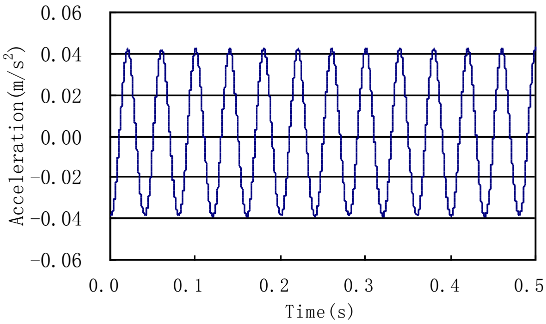


Fig.7.(a) The time domain signal of the standard sensor system (b) The time domain signal of FBG sensor system

Experimental data shows that this FBG sensor system can realize the measurement of micro-vibration and has better measurement effect. Fig. 8 shows the frequency domain output of the system when the FBG2 sensor is applied with no signals. The noise level of the system is 1mm/s^2 from Fig.8, then the FBG2 sensor system can detect the smallest acceleration of 1mm/s^2

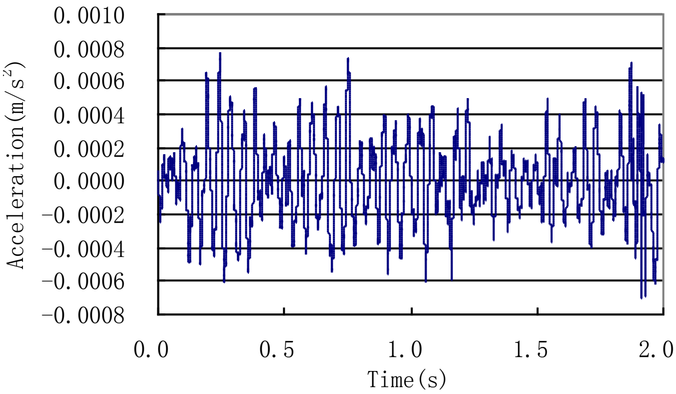


Fig. 8 the frequency domain output of the FBG system applied with no signals

5. Experiment Results in Coal Mine

The exepriment is applied on coal mine in BaoDian, ShanDong, Province. Eight Fiber micro-seismic sensors are installed on the coal mine. Fig.9 exhibits the setting location below coal mine of the seven sensors. The longest distance is about six kilometers. The shortest distance is three kilometers. The eighth sensor is installed on top of the coal mine. Fig 10 shows the FBG sensor setted on coal mine. These FBG sensors are fixed on a anchor-pole which are insertted into the coal-bed. Fig 11 represents the micro-seismic signals obtained by the FBG sensor system. The micro-seismic signals is a series of signals whose frequencies sre mainly between 5 and 40Hz. The experiments on coal mine exhibit that the FBG sensor can be used to measure micro-seismic sigmals. But there are many problems too, such as orientation, sensor coupling with the coal-bed.

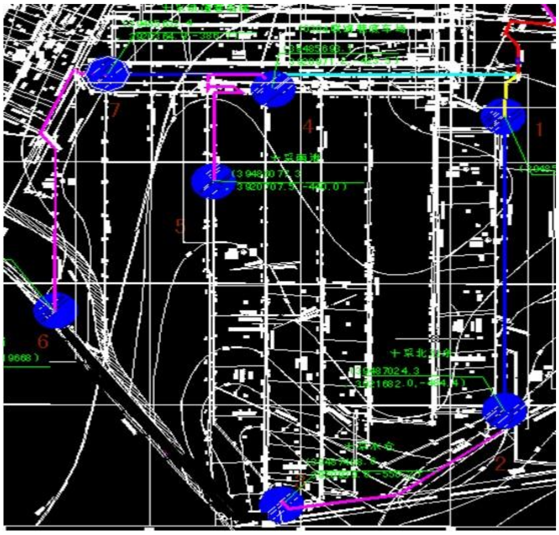


Fig.9 The setting location below coal mine of the seven sensors

Fig.10 The FBG sensor installed

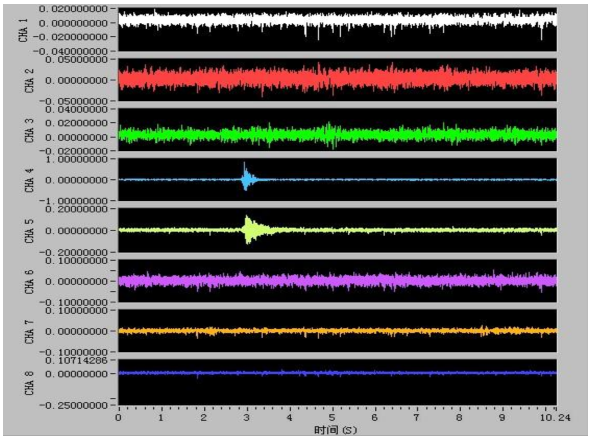


Fig. 11 The micro-seismic signals got by the FBG system

6. Conclusions

This paper introduces an filtering interrogation scheme for FBG vibration sensor. The interrogation scheme takes advantage of the intensity modulation of narrow spectral bandwidth light of the DFB laser output. The FBG is both an vibration sensor and a filter element for demodulation.The sensitivity of the sensor system is discussed in detail and according to this, a high sensitivity FBG sensor is factured. The system can reach the minimum of the acceleration measurement of 1mm/s^2.

The system can be used to demodulate dynamic strain of FBG sensor. It is simple, low cost, and has high sensitivity, and easy to have practical use in the future. The experiments on coal mine shows that the

FBG sensor can be applied to measure micro-seismic sigmals.

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